Fermi National Accelerator Laboratory

J/ψ and $\psi\prime$ Production at CDF

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This paper presents measurements of the J/ψ and ψ' production cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The cross sections are measured in the kinematic region $P_T > 5$ GeV/c, $|\eta| < 0.6$ using the dimuon decay channel. The fraction of events from B decays is measured and used to calculate the J/ψ and ψ' cross sections from B decay. The fraction of J/ψ events from χ_c decays is also measured and used to calculate the J/ψ cross section from direct production.

In this paper we report a study of the reactions $p\bar{p} \to J/\psi X$, $p\bar{p} \to \psi' X$ and $p\bar{p} \to \chi_c X$; $\chi_c \to J/\psi\ \gamma$ where the J/ψ and ψ' mesons decay into two muons. The study is performed at $\sqrt{s} = 1.8$ TeV with the CDF detector at Fermilab. Charmonium production is currently the best way to study b quark production at CDF at the lowest possible transverse momentum of the b. The rates of J/ψ production from χ_c decays and of direct J/ψ and ψ' production are also very interesting as there have been large discrepancies between the observed rates [1,2] and the color-singlet predicted rates [3–5].

The CDF detector has been described in detail elsewhere [6,7]. The components relevant to this analysis are briefly listed here. The Silicon Vertex Detector (SVX) surrounds the beam pipe and allows the identification of secondary vertices. The

central tracking chamber (CTC), embedded in a 1.4 T axial magnetic field, provides three dimensional track reconstruction. Surrounding the CTC are the central electromagnetic (CEM) and hadronic (CHA) calorimeters providing five absorption lengths of material before the muon chambers. The Central Muon Chambers (CMU), covering the pseudorapidity region $|\eta| < 0.6$, are complemented by a system consisting of four layers of drift tubes behind 2 feet of steel (CMP). The central electromagnetic strip chambers (CES) are located at a depth of six radiation lengths inside the electromagnetic calorimeter.
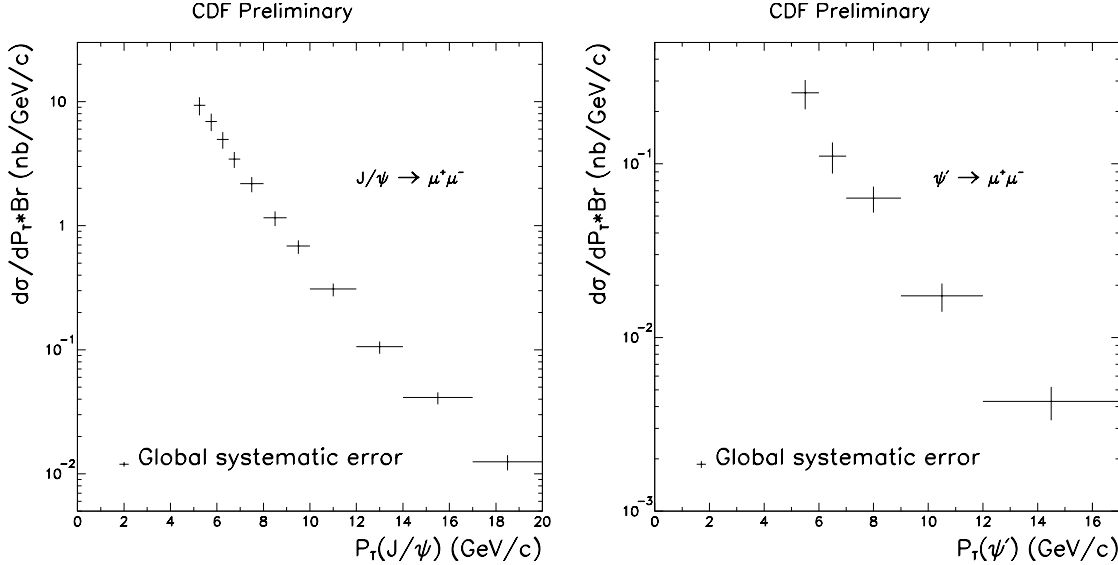
FIG. 1. Differential cross sections of J/ψ (left) and of ψ' (right) as a function of P_T and in the region $|\eta| < 0.6$.

We have reconstructed the J/ψ and ψ' mesons in the dimuon mode and in the kinematic region $P_T > 5$ GeV/c, $|\eta| < 0.6$. Both muons are required to come from a common vertex. If there are at least three hits in the SVX associated with a muon track, the information is used to improve the measurement of the track. Both muons are required to have $P_T^\mu > 2.0$ GeV/c and one muon must have $P_T^\mu > 2.8$

GeV/c. We find $22,120 \pm 161$ J/ψ events in 15.4 pb^{-1} of data and 808 ± 46 ψ' events in 17.8 pb^{-1} of data. Fig. 1 shows the differential J/ψ and ψ' cross sections as a function of P_T in the pseudorapiduty region $|\eta| < 0.6$. The error bars represent the statistical and P_T dependent systematic uncertainties added in quadrature. We find that $\sigma(p\bar{p} \rightarrow J/\psi X) \cdot Br(J/\psi \rightarrow \mu^+\mu^-) = 17.35 \pm 0.14(\text{stat})^{+2.59}_{-2.79}(\text{sys})$ nb and $\sigma(p\bar{p} \rightarrow \psi'X) \cdot Br(\psi' \rightarrow \mu^+\mu^-) = 0.571 \pm 0.036(\text{stat})^{+0.082}_{-0.089}(\text{sys})$ nb for $P_T > 5$ GeV/c and $|\eta| < 0.6$. Using SVX information to reconstruct the decay vertices of the charmonium states, we distinguish between charmonia from B decays and from other production mechanisms. The SVX detector covers the luminous region of $|z| < 26$ cm along the beam line and only about 50-60% of the tracks found by the CTC have SVX information. Therefore, in order to decrease the statistical errors on the measurement of the fractions of charmonia coming from B decays, a larger data sample, of $\sim$110 pb^{-1}, was used for those studies. This additional statistics are not used for the cross section measurements because some efficiencies are still under study. We find that for the kinematic region $P_T > 5$ GeV/c and $|\eta| < 0.6$, $(19.2\pm0.2(\text{stat})\pm0.4(\text{sys}))\%$ of J/ψ's and $(23.3\pm1.8(\text{stat})\pm0.5(\text{sys}))\%$ of ψ''s come from the decay of b hadrons. In Fig. 2 we show the differential production cross section measurements from B decays and compare them with the NLO QCD theoretical predictions. These cross sections are extracted by convoluting the differential B fraction with the differential J/ψ and ψ' cross sections. We see that the experimental measurements are a factor of 3-4 above the central value of the theoretical predictions. By using the inclusive production cross sections of J/ψ and ψ' and the fraction of these mesons produced from B decays we have also determined the b-quark production cross section (see

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Table 1) in the rapidity range $|y^b| < 1.0$ and for $P_T^b > P_T^{min}$; P_T^{min} is chosen in such a way so that 90% of the produced $J/\psi[\psi']$ have $P_T^b > P_T^{min}$. We have found as well that $\frac{Br(B \to \psi' X) \cdot Br(\psi' \to \mu^+ \mu^-)}{Br(B \to J/\psi X) \cdot Br(J/\psi \to \mu^+ \mu^-)} = 0.033 \pm 0.003(\text{stat}) \pm 0.002(\text{sys})$.
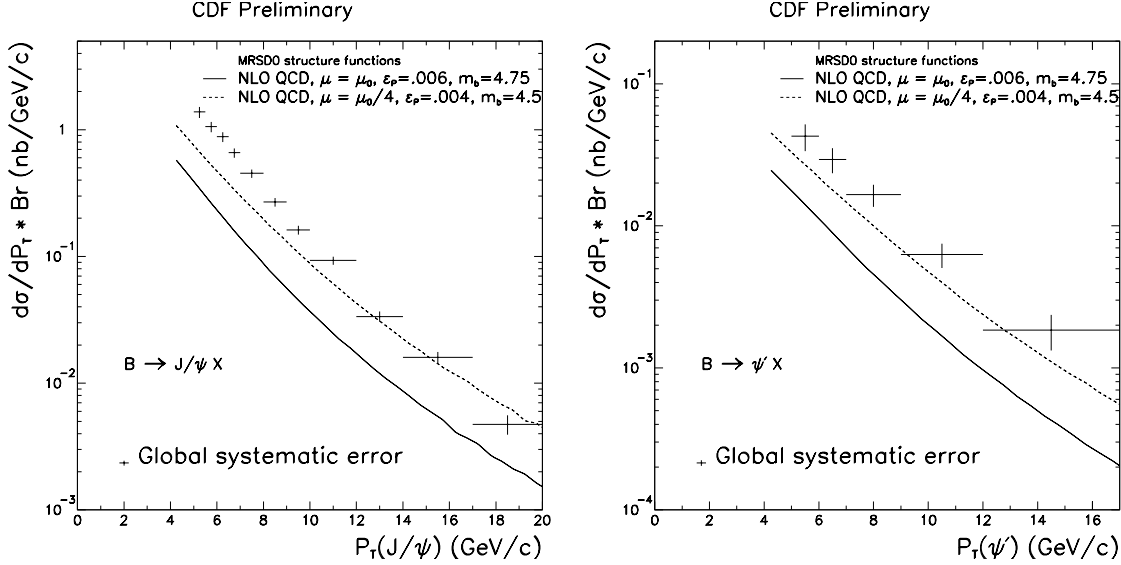

FIG. 2. Differential cross sections from B production of J/ψ (left) and of ψ' (right) as a function of P_T and in the region $|\eta| < 0.6$. The solid and dashed curves are the NLO QCD theoretical expectation.

During the past couple of years it was established that the observed CDF yield for J/ψ's and ψ''s not originating from B decays is much larger than the theoretical expectation from direct production models including contributions from charm fragmentation and gluon fragmentation from color-singlet diagrams. The disagreement with the theory is much more prominent in the ψ' state (a factor of ~ 50) and it has created intense theoretical interest. It triggered additional theoretical work and for the first time the color-octet fragmentation diagrams [8–10] were considered as a possible solution for the J/ψ and ψ' anomalies. CDF is able to test these theoretical

assumptions for both the J/ψ and ψ' states. This became possible, especially for the J/ψ, since we measured the fraction of J/ψ's from χ_c decays.

P_T^{min} GeV/c	$\sigma(\mu b)$	Mode
7.6	6.98 ± 0.82	J/ψ
9.0	4.49 ± 0.52	J/ψ
10.4	2.83 ± 0.33	J/ψ
11.7	1.87 ± 0.22	J/ψ
13.0	1.25 ± 0.15	J/ψ
14.4	0.832 ± 0.10	J/ψ
7.5	6.8 ± 2.3	ψ'
8.8	4.7 ± 1.6	ψ'
10.1	3.3 ± 1.1	ψ'
12.8	1.6 ± 0.6	ψ'

TABLE 1: b-quark cross sections for $|y^b| <1.0$ and $P_T^b > P_T^{min}$

The fraction of J/ψ's from χ_c decays is measured by reconstructing the decay $\chi_c \rightarrow J/\psi \, \gamma$ in ~ 18 pb^{-1} of data. We select photon candidates by demanding an electromagnetic energy deposition of at least 1 GeV in a CEM calorimeter tower and a cluster in the fiducial volume of the CES chambers. We also require that no tracks point to the tower corresponding to the photon candidate. The location of the cluster in the CES chamber and the event interaction point determine the direction of the photon momentum, whose magnitude is the energy deposited in the calorimeter cell. The J/ψ is combined with photon candidates to form the invariant mass difference distribution, $\Delta M = M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$, which is shown in Fig. 3. A clear

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χ_c signal of $1,230 \pm 72$ events is present near $\Delta M = 400$ MeV/c^2 but the detector resolution is not good enough to resolve the individual χ_{c1} and χ_{c2} states which are separated by 45.6 MeV/c^2. The shape of the background is obtained with a Monte Carlo method that uses real J/ψ events as input. This model was tested, for dimuon pairs in the sidebands of the J/ψ peak where there is no χ_c signal, by comparing the distribution obtained in this way with the one directly obtained from the data.

We find that the fraction of J/ψ's coming from χ_c's, integrated for $P_T^{J/\psi} > 4$ GeV/c and $|\eta^{J/\psi}| < 0.6$, is $F_\chi^{J/\psi} = 28.3 \pm 1.6(stat) \pm 6.8(syst)$ %. This fraction includes a contribution from $B \to \chi_c\ X$ and $B \to J/\psi\ X$ decays. We remove this contribution by using the cross section of J/ψ from b's measured by CDF and branching ratios of B mesons to charmonium states measured by CLEO [11]. We find that the fraction of J/ψ's with $P_T^{J/\psi} > 4$ GeV/c and $|\eta^{J/\psi}| < 0.6$ coming from χ_c's and not including contributions from $B \to J/\psi X$ and $B \to \chi_c X$ decays is $F(Nob)_\chi^{J/\psi} = 32.3 \pm 2.0(stat) \pm 8.5(syst)\%$. In Fig. 3 we show this fraction as a function of $P_T^{J/\psi}$. These results imply that the production from χ_c's is not the dominant production mechanism of prompt J/ψ's, in disagreement with current theoretical predictions according to which χ_c's are expected to be the main source ($> 90\%$) of prompt J/ψ's.

The cross section of J/ψ's from χ_c's is obtained multiplying our inclusive prompt J/ψ cross section with a parametrization of $F(No\ b)_\chi^{J/\psi}$ as function of $P_T^{J/\psi}$. The cross section for prompt J/ψ's not from χ_c's, is obtained by subtraction. The prompt J/ψ from χ_c component is in reasonable agreement with the theoretical calculation. The prompt J/ψ not from χ_c cross section is a factor ~ 50 above the color-singlet

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calculation. This indicates that the color-singlet model underestimates direct production of the J/ψ by the same factor found for the ψ' and that direct production is the dominant production mechanism of prompt J/ψ's.
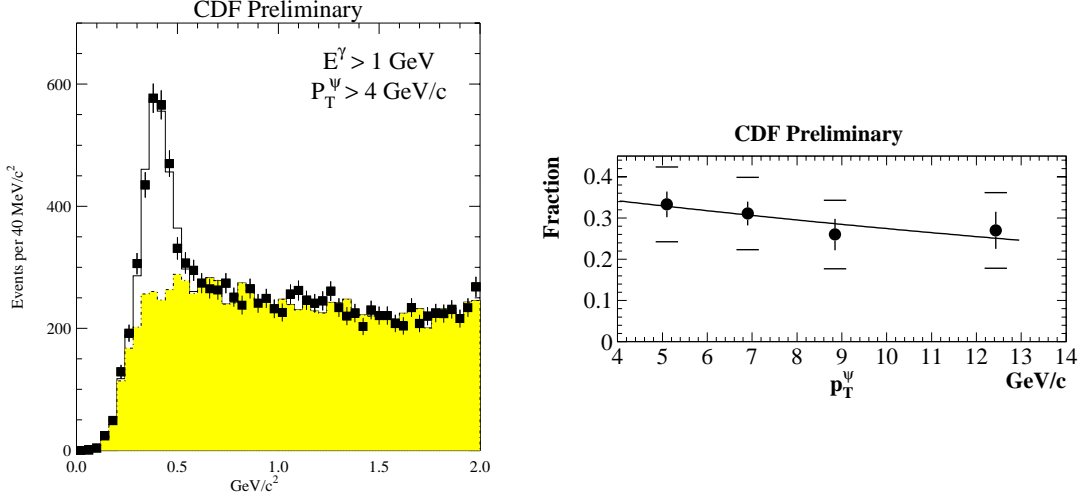

FIG. 3.   On the left, the mass difference $M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ for the J/ψ signal region. On the right, the fraction of J/ψ from χ_c as a function of $P_T^{J/\psi}$ with the contribution from b's removed. For both plots calorimeter information is used for the detection of the photon, and $P_T^\gamma > 1 \ GeV/c$.

The direct, differential J/ψ and ψ' cross sections are shown in figures 4 and 5. The open circles represent the data. The B and χ_c components have been removed from the J/ψ cross section and the B component has been removed from the ψ' cross section. The theory curves are from Ref. [9]. The dashed curves represent the prediction for the color-singlet model. The ψ' feeddown curves in the J/ψ cross section plots are properly normalized contributions from the decay $\psi' \rightarrow J/\psi\pi^+\pi^-$. The dotted curves correspond to the production in the $^3S_1$ color-octet state and the dashed-dotted curves to the production in the $^3P_0$ and $^1S_0$ color-octet states.

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The shapes of these color-octet cross sections are calculated perturbatively. The normalization nevertheless depends on non-perturbative matrix elements, for which there exist only order of magnitude predictions, and therefore the matrix elements are derived from fits to the CDF data. The simplest approach is to attempt to fit the J/ψ and ψ' independently, except that the ψ' feeddown to the J/ψ is normalized by the ψ' results (see Fig. 4). In this fit, the fraction of prompt J/ψ's from χ, $F(Nob)_\chi^{J/\psi}$, the acceptance, the trigger efficiency and the branching ratios involved in the ψ' feeddown contribution are allowed to vary within one sigma. In this case, the ψ' $^3S_1^{(8)}$ contribution dominates the ψ' fit. While the $^1S_0^{(8)}, ^3P_0^{(8)}$ matrix element has a large error, it is of the same order of magnitude as the $^3S_1^{(8)}$, as expected. The same is true for the J/ψ fit (ratio is about 1:3). There is a 20% deviation at high P_T but the overall agreement with the data is good.
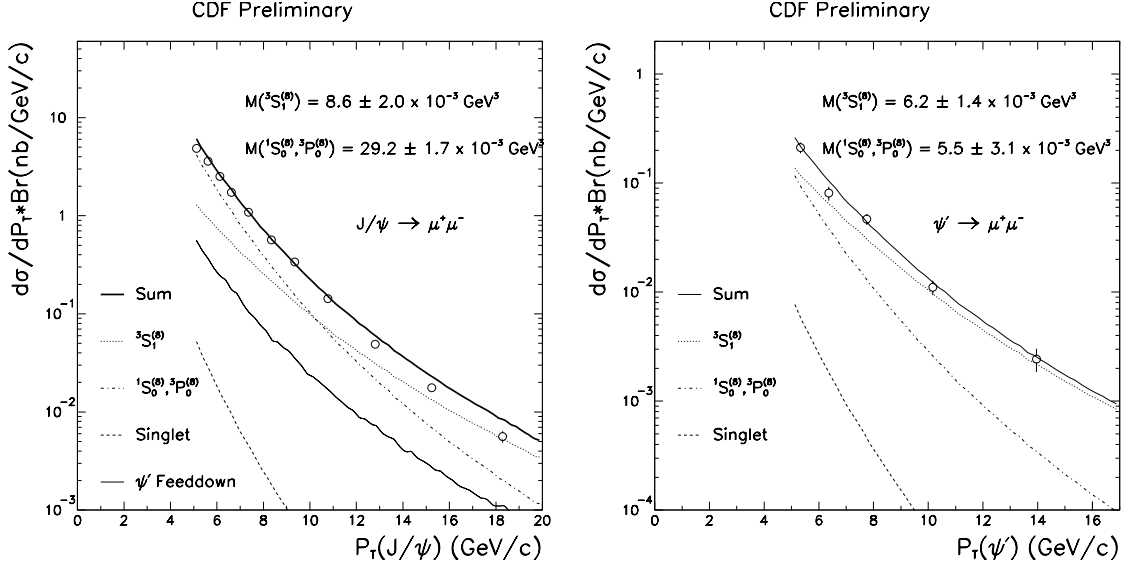

FIG. 4. Direct, differential cross sections of J/ψ as a function of $P_T^{J/\psi}$ (left) and of ψ' as a function of $P_T^{\psi'}$ (right). The B contribution has been removed from both J/ψ and ψ' and the χ_c contribution has been removed from J/ψ. The fit with the color-octet shapes is done independently for J/ψ and ψ'.
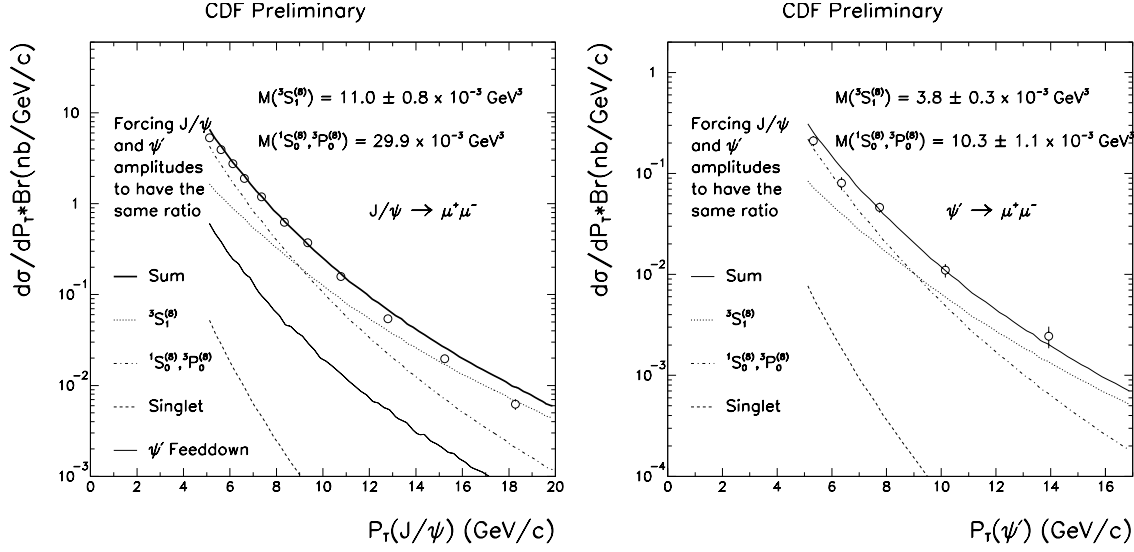
FIG. 5. Differential cross sections of J/ψ as a function of $P_T^{J/\psi}$ (left) and of ψ' as a function of $P_T^{\psi'}$ (right). The B contribution has been removed from both J/ψ and ψ' and the χ_c contribution has been removed from J/ψ. The fit with the color-octet shapes is done simultaneously for J/ψ and ψ'. The ratio of the $^3S_1^{(8)}$ and $^1S_0^{(8)}, ^3P_0^{(8)}$ amplitudes has been required to be the same for J/ψ and ψ'.

A more complex approach is to simultaneously fit the J/ψ and ψ' curves (see Fig. 5). In this fit all the corellations between the J/ψ and the $\psi(2S)$ are taken into account. Since the theory predicts that the $^3S_1^{(8)}$ and the $^1S_0^{(8)}, ^3P_0^{(8)}$ amplitudes should be similar for the J/ψ and ψ', we impose the additional constraint that the ratio of the two amplitudes be the same for J/ψ and for ψ'. Although the fit is above the J/ψ data at high P_T, the overall agreement with the data is good.

In conclusion, we have measured the differential and integrated inclusive J/ψ and ψ' cross sections and their components from B decay and from prompt production. We have also measured the fraction of J/ψ's originating from χ_c's and found that the

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majority of prompt J/ψ's do not come from χ_c's but is directly produced. Using this χ_c fraction we measured for the J/ψ the direct component of the prompt cross section and we concluded that the color-singlet model fails to describe direct production for both the J/ψ and the ψ' by the same large amount. The color-octet mechanism seems to help explain some of the discrepancies. Much more experimental and theoretical work is necessary though in order to show conclusively that the quarkonia production mechanisms are understood.

[1] The CDF Collaboration, "Study of Production Mechanisms of J/ψ and $\psi(2S)$", FERMILAB-CONF-94/136-E.

[2] The CDF Collaboration, "Production of J/ψ from χ_c decays at CDF", FERMILAB-CONF-95/226-E.

[3] R. Baier and R. Rückl, Z. Phys. C **19**, 251 (1983).

[4] E. Braaten, M. Doncheski, S. Fleming, M. Mangano, Phys. Lett. **B333**, 548 (1994).

[5] M. Cacciari, M. Greco, Phys. Rev. Lett. **73**, 1586 (1994).

[6] F. Abe et al., Nucl. Instr. Meth. **A271**, 387 (1988).

[7] D. Amidei et. al., Nucl. Instr. Meth. Phys. Res., Sect. **A350**, 73 (1994).

[8] E. Braaten and S. Fleming, Phys. Rev. Lett. **74**, 3327 (1995).

[9] P. Cho and A.K. Leibovich, Phys. Lett. **D53**, 150 (1996),

P. Cho and A.K. Leibovich, Phys. Rev. **D53**, 6203 (1996).

[10] M. Cacciari, M. Greco, M. L. Mangano, A. Petrelli, Phys. Lett. **B356**, 553 (1995).

[11] R. Balest et al., "Inclusive Decays of B mesons to Charmonium", CLNS 94/1315.